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Wiring Damage Analyses for STS OV-103

Walter Thomas, III

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Contents

List of Tables

List of Figures

EXECUTIVE SUMMARY

This study investigated the Shuttle Program's belief that Space Transportation System (STS) wiring damage occurrences are random, that is, a constant occurrence rate. Using Problem Reporting and Corrective Action (PRACA)-derived data for STS Space Shuttle OV-103, wiring damage was observed to increase over the vehicle's life. Causal factors could include wiring physical deterioration, maintenance and inspection induced damage, and inspection process changes resulting in more damage events being reported. Induced damage effects cannot be resolved with existent data. Growth analysis (using Crow-AMSAA, or CA) resolved maintenance/inspection effects (e.g., heightened awareness) on all wire damages and indicated an overall increase since *Challenger* Return-to-Flight (RTF). An increasing failure or occurrence rate per flight cycle was seen for each wire damage mode; these (individual) rates were not affected by inspection process effects, within statistical error. Preliminary analyses of FAA data on civil aircraft wiring incidents showed Weibull β's of 1.6 to 1.9, indicating these craft incurred increasing wire failures over time.

OV-103 data were analyzed to determine wiring inspection-maintenance process behavior and whether *Discovery* experienced increasing wire damage over its life. Induced damage events, as defined by the event record descriptions in the avionics wiring database, were only 15% of wiring damage events; this is significantly different than the 85 to 90% cited by the Program. "Common cause events," those affecting more than one wire, were 14% of all events. The most frequent occurrences were exposed conductors and Kapton™ damage.

CA analyses of OV-103's wiring inspection and maintenance process showed the process was not consistent over the vehicle's life. The longest stable run was five flight cycles. After the J1 major maintenance, wire damage detection oscillated between "enhanced" detection (CA slope greater than 1) and "diminished" detection (slope less than 1). Detected events gradually increased from 20 per flight cycle after *Challenger* RTF to 40 per cycle before the *Columbia* accident. The cited six-fold detection improvement after the July 1999 stand-down was not verified; the CA occurrence rate showed a 1.3 times improvement.

Six wiring failure modes, analyzed discretely, showed all exhibited Weibull β's (slope parameters) indicating early wear-out failure modes (failure rates increasing over time) after 63 to 99 months. These β's ranged from 1.7 to 3.7, depending on the failure mode. Before early wear-out modes commenced, damage events were infant mortality or near constant-failure-rate (CFR) failures; β's were 0.4 to 0.9. Weibull results indicated that OV-103's ***wiring accumulates more damage over time,*** that is, wire damage failure or occurrence rates increased over time. Weibull parameters for the two modes relevant to the inadvertent firing scenario are: wiring short circuits β = 1.7 and η = 226,540 months; and exposed conductors, early distribution β = 0.9 and η = 23,069,140 months and later distribution β = 2.2 and η = 8911 months. These parameters should be used to revise the NESC fault tree model.

Wiring damage for OV-104 and OV-105 should be evaluated using the protocol in this report. Inspection-maintenance process analysis using CA is urged for OV-104 and OV-105. Trending wire damage should benefit the Program immensely. Wiring damage inspection-maintenance changes that yield a stable process (evidenced by a continuously fitted CA plot, without jumps or slope changes) would produce predictable wiring damage occurrences. Likely, CA could be used in other aspects of the Program for trending important events or activities.

It is unrealistic to expect all wiring to be replaced in the vehicles. Per NESC recommendation, if the Program replaces the Reaction Jet Driver (RJD) wiring, they should expect either infant mortality or CFR failures for five to eight subsequent years, depending on the wire failure mode, for that "new" wiring. Because wire damage does increase as the vehicle matures, the Program should critically evaluate "CRIT 1-1" wiring and closely monitor its damage to prevent future undesirable events.

I. Introduction

The NESC was tasked with reviewing and assessing risks for an inadvertent firing of the Space Shuttle Reaction Jet Drivers whilst the vehicle was mated with the International Space Station (ISS) [1]. Part of this investigation focused on the potential for a wiring short circuit causing an inadvertent firing. The Shuttle vehicles each contain approximately 147 to 150 miles of wiring, most of which has Kapton™ insulation. This aromatic polyimide insulation is, and has been, used in aircraft and spacecraft for decades because it is "lightweight, nonflammable, has a wide operating temperature range and resists damage" [2]. However, it is subject to degradation through improper installation, mishandling, and upon exposure to moisture [3].

NESC analyses showed civil aircraft wiring is subject to effects with its time span, that is, wiring failure incidents (short circuits, wire breaks, chafed wires) increased with the aircraft life cycle (see Section **II**, below). The Program, however, has maintained the Shuttles are not subject to wire deterioration over time and that most wire damage occurrences are related to maintenance activities. They have cited extreme differences in maintenance procedures and operational profiles compared to civil aircraft as rationale that Shuttle wiring is not subjected to deterioration.

The NESC assessment developed a fault tree model for the inadvertent firing scenario, for which one branch details the various wiring events or incidents likely to affect the inadvertent firing scenario. No accurate data were available, however, for the frequencies or probabilities (of occurrence) for the precipitating, or bottom level, events. These probabilities are needed to accurately assess their effects on the undesired end (or "top level") event—inadvertent firing.

As extensive records regarding Space Shuttle wiring damage events were available, these data were analyzed to determine if one Orbiter did incur wire degradation (i.e., more damage over time) and, if so, to derive the statistical distributions related to the various failure modes. Data available for OV-103 (*Discovery*) were used to compute the frequencies and probabilities of wire damage events. These results were used to refine the fault tree model (also called a probabilistic risk assessment or PRA).

Because the civil aircraft wiring analyses, cited above, provided the impetus for analyzing STS vehicle wiring, they are included herein. Data and analyses procedures used to compile and analyze OV-103 wiring are described in detail. Then, results are presented for both the wiring events—wiring maintenance/inspection process (CA analyses) and wiring damage failure distributions by modes (Weibull analyses). The details reported herein should be sufficient to enable the Program to perform similar analyses and predictions for the other two STS vehicles.

II. Civil Aircraft Wiring Incidents

A previous STS report [4] had reviewed Federal Aviation Administration (FAA) wiring incidents involving civil aircraft. However, only the number of incidents was counted to estimate a Poisson statistic for wiring shorts. Evidently, this work did not perform a detailed analysis to determine whether the counted FAA incidents were relevant to wire aging.

NESC performed a more extensive examination of FAA data to determine when reported wiring incidents occurred (by aircraft operating hours) and the consequent failure characteristics. A Weibull plot can indicate whether failures (e.g., wiring "incidents") occur with a decreasing failure rate (infant mortality), a constant failure rate (CFR—occur randomly over time), or with an increasing failure rate. The FAA maintains its Aircraft Incident Data System (AIDS) database containing over 82,500 records of aircraft incidents from 1978 to the present (May 2004, when these data were compiled) [5]. These are reported "incidents" for which a report was filed with the FAA. The Federal Air Regulations (FARs) cite specific definitions for aircraft "incidents" and requirements for when reports must be filed.

FAA records were searched using keywords related to wiring events and each incident description was reviewed to determine its relevance to the life of the wire. For example, "short circuits" *resulting from* engine fires or spilled drinks were discounted, as was "…a large dog escaping his container in the cargo hold and chewing through numerous wire harnesses…" Thus, only "primary cause" (that is, non-*consequential*) wire events consistent with wire degrading over time were compiled. Table I summarizes these results.

Table I. Data compiled from FAA "AIDS"

Type*	Keyword	# "hits"	# relevant	# relevant w/ airframe hours
91, 121, 135	"wiring"	158	49	28
	"short circuit"	11	1	1
	"short"	175	*not analyzed further*—too many not relevant	
	"wire"	887	*not analyzed further*—insufficient time	
121 & 135 only	"wire"	134	62	46
121 & 135 only	"shorted"	95	41	19

* 91 = general aviation, 121 = air carrier, 135 = air taxi/charter (i.e., commercial)
NTSB database ("accidents") not used; airframe hours not cataloged and database difficult to query in a timely manner.

The initial analysis evaluated wiring incidents for both general aviation (GA) and air carrier/commercial (AC/C) aircraft. A Weibull plot of these data is shown in **Figure 1**. Both GA and AC/C wiring exhibited slopes ("β's") of 1.8 and 1.9 (statistically the same at 90%

confidence). The greater-than-1 slope indicates an *increasing* failure rate; that is, wiring incidents are occurring more frequently as aircraft accumulate operating hours. The identical slopes imply failures occurred with similar modes (failure mechanisms). Characteristics lives ("η") were 9020 and 31,200 airframe hours, respectively. The behavior of characteristic lives is very interesting. Generally, AC/C aircraft accrue considerably more operating hours per calendar year than GA aircraft; thus, one would expect the AC/C failure distribution to coincide or precede that for GA aircraft. The AC/C plot, however, is displaced approximately 20,000 hours <u>*later*</u>. This suggests a causal factor other than aircraft operating hours, when GA and AC/C are compared. (No data were available for aircraft calendar ages at the event times). Nonetheless, these data do show that civil aircraft wiring incidents exhibit an increasing failure rate with time.

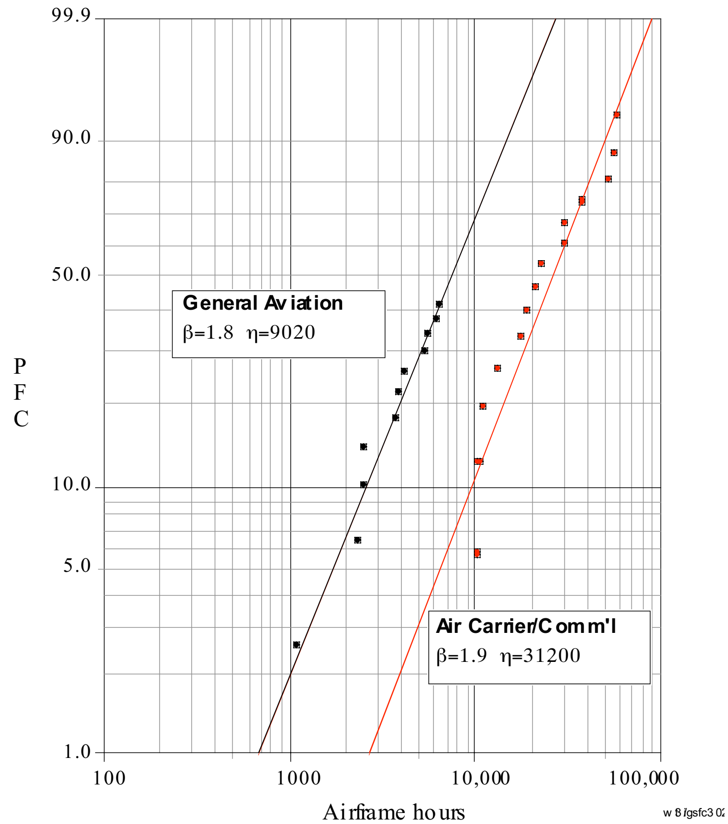

Figure 1. Weibull plot of civil aircraft wiring "incidents." Data for both GA and AC/C aircraft have the same slope, but are displaced along the time axis.

Subsequent analyses of the FAA data focused on air carrier and commercial operations only. Additional data were compiled, producing the following numbers of relevant wiring incidents for AC/C aircraft:

Table II. Numbers of Wiring and Wire Shorting Events for Air Carrier and Commercial Aircraft

N/A or unspecified**	Wiring			# w/ airframe hrs. ***
	Shorts (circuits)	Chaffed	Broken	
59	104	22	36	64
Usable for	Weibull analyses:			
(11)	16	10	10	42

** N/A = not applicable: other components shorted, wire failures with non-aging causes; "unspecified" means wiring failure description not specific enough to assign one of the above failure modes.

*** Not all events with airframe hours reported were associated with wire failures; some were associated with other component failures.

Initial analysis of these data showed an approximate fit to a constant failure rate (CFR) model, i.e., the Weibull slope was near 1.0 (see **Figure 2)**; however, the data fit was poor. Abernethy [6] points out that a CFR distribution can "hide" a mixture of failure modes. That is the case for these data. Re-plotting by separating failures by mode produced the **Figure 3** plot. Here, the data fit improved. All three failure modes yielded a Weibull slope of 1.6 ("early wear-out"); they were displaced slightly along the time axis. This, again, indicates an ***increasing failure rate*** for civil AC/C wiring failures.

Note that **Figures 1** through **3** plot cumulative failure occurrences versus airframe hours at each occurrence. The "cumulative failure probability" (y-axis) is actually a cumulative probability of failure within the population of failure events, ***NOT*** the field (or in-service fleet) failure probabilities caused by wire incidents. To derive a "fleet" failure distribution, cumulative operating hours for all in-service aircraft by type (i.e., model), which did *not* experience wire failures, are needed. That data was unavailable. Including these data simply will move the Weibull plots down the cumulative failure probability axis, because the non-failed aircraft hours would be "right censored." That is, non-failed data are not plotted, but they are accounted in the probability computations. The Weibull slopes (β's) would be unaffected [7].

The following conclusions can be drawn from the civil aircraft data:

(1) General Aviation and AC/C wiring failure events had the same Weibull slopes, β = 1.8 – 1.9, indicating early wear-out failure modes.

(2) Wiring failures in AC/C aircraft exhibited three failure modes: shorted, chafed and broken. These modes showed the same early wear-out slope (β = 1.6) and were displaced slightly along the time axis.

(3) All data exhibited Weibull slopes indicating early wear-out failure modes.

(4) A *constant failure rate model* is ***neither representative nor accurate*** for civil aircraft wiring failures.

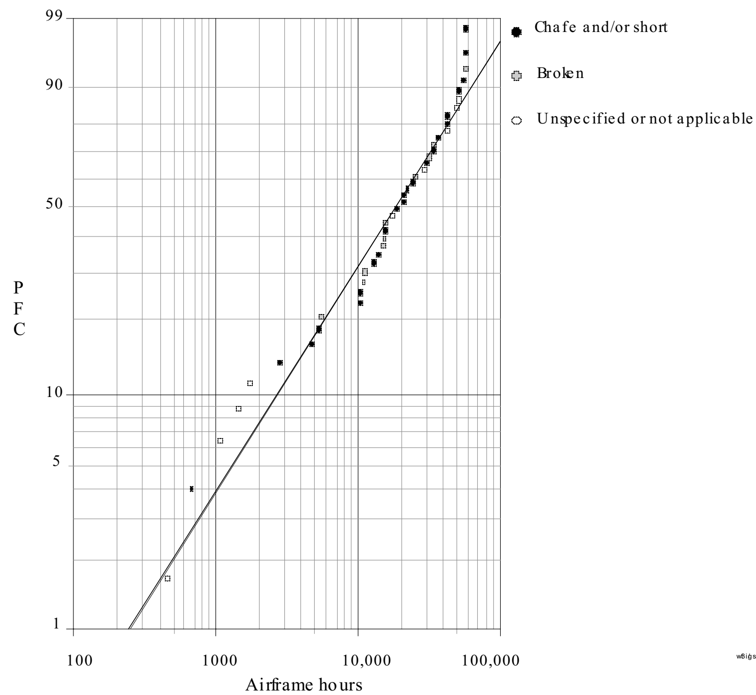

Figure 2. Weibull plot of Air Carrier and Commercial aircraft wire failure incidents. Apparent Weibull slope (β—the dashed line) is ~1, but data clearly indicates mixture of failure modes (plot is not linear). Failures are coded according to legend in upper right.

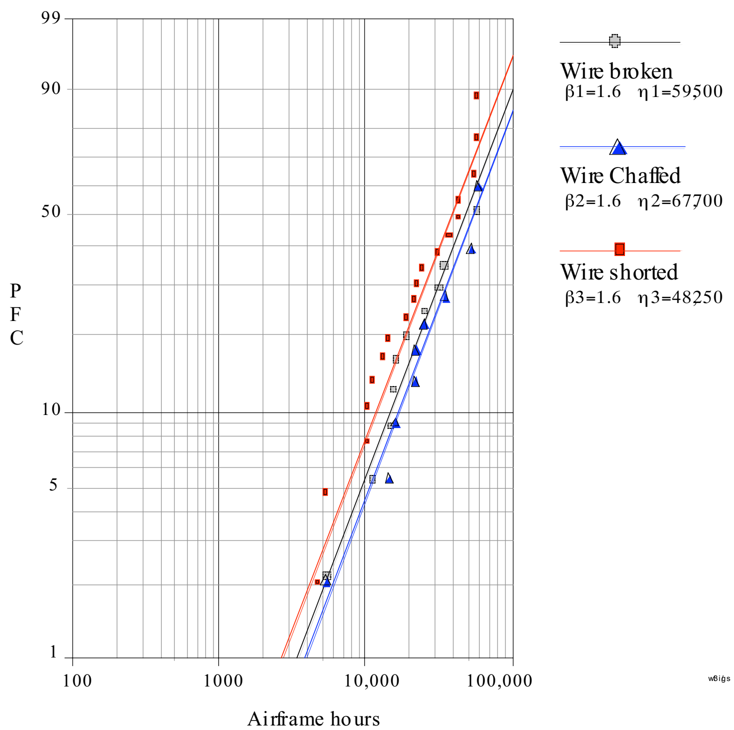

Figure 3. Weibull plots of Air Carrier and Commercial Operations wiring failure incidents separated by failure modes. The three modes have the same Weibull slopes and are displaced slightly along the time axis. Wiring failures are *not consistent* with a constant failure rate model.

III. OV-103 Wiring Data—Initial Compilations

The Program maintains extensive records regarding incidents and maintenance of the STS vehicles. For OV-103, records regarding wiring events from early 1984 through August 2004 were provided [8], and derived from the Kennedy Space Center's "Avionics Database." Records were forwarded as three separate files, which were then merged. These files had no data for January through December 2002 or January through April of 2003. This initial file contained approximately 5,400 records. Non-relevant data fields (for these analyses) were deleted.

Each record was reviewed and those not relevant to wiring damage (e.g., connector damage) were deleted. Most, but not all, of these non-relevant records corresponded to the Program's "NW" (non-wire) coding. Simultaneously, wire damage codes were assigned to each of the remaining 2,490 records. These codes were derived to describe accurately wiring damage consistent with the wording in the event descriptions; they are somewhat more detailed than the Program's codes. The damage codes assigned are shown in **Table III**. These are labeled "**NESC Code**," to distinguish them from Program-assigned codes.

Table III. NESC Wiring Damage Codes

NESC Code	Damage Description
KD	Kapton™ damage, unspecified
KR	Kapton™ cracked or ring cracks
KS	Kapton™ damage with shield exposed
KX	Kapton™ damage with exposed conductors
WB	Wire broken
WC	Wire conductor damage
WD	Wire damage, unspecified
WF	Wire chafed, or wire with chafe protection needed
WI	Wire insulation damage (not specified as "Kapton")
WJ	Wire jacket damage (outer jacket damaged)
WS	Wire damage with shield damage
WT	Wire shorted (short circuited)
WU	Wire cut
WX	Wire with exposed conductor

Some reported events had wire damages fitting more than one category. For example, one description cited "…FOUND WIRE INSULATION IS CUT AND THERE IS DAMAGE TO CONDUCTOR." A separate field was created to accommodate multiple event modes for one event; thus, the above-cited event was coded "WC" and "WU".

Another field was added to record "induced" damage events—those for which the description indicated clearly that the wire damage was induced, or caused, by other than "natural" factors. For instance, "cut" wires (usually inadvertently) were damage caused by inspection or maintenance actions. These were assigned "I" for induced. "Severed" wires were included as "WU", or cut, and all "scuffed Kapton™" were cataloged as I for induced [9]. Numerous events cited "impact damage" (wire damage caused by something or someone having impacted a wire

or wires) and these were assigned "I." Descriptions indicating damage events caused by previous maintenance or repair actions were coded as "IR" for induced repair.

The record date was used as the occurrence date for each event. The occurrence time was calculated as the time between vehicle delivery (10 November 1983) and the record date. Times were computed as *months*. [Computations performed in the spreadsheet database yielded numbers of days; these were converted to months by dividing by 30.43 (= 365.25/12) days per month.] For each record, a field was created listing the occurrence time (in months) from vehicle delivery.

The database then was reviewed and duplicate events (that is, those having two or more reports for the same event) deleted. This revision yielded approximately 1,938 damage records affecting 2,510 wires. Next, "previous events" for each given wire number and location were evaluated. If a wire number was reported previously (chronologically) in the database, it was researched to determine if the previous event corresponded to the same location. For this analysis, the "same location" was assumed to be within one digit of the "ones" digit (far right-hand number) in the three-digit location identifier. (Not all events had wire locations specified with x-y-z coordinates). Events occurring at the same location were tracked back to the original (first occurring) event and subsequent event records deleted. This relates to "PES" ("prior event-same location") referenced in **Table IV**; thus, *the revised database compilation represents only original occurrences of all wiring damage events*. These revisions yielded 2,125 damage events among 2,510 affected wires.

From these data, frequency statistics were compiled regarding the frequencies of occurrences for the different failure modes (i.e., codes). Because of the July 1999 STS-93 system malfunction,* which prompted the "wiring stand-down"[10], data were compiled for two periods: March 1984 through May 1999, and July 1999 through August 2004. Wiring damage event frequencies are cataloged in **Table IV**, **Summary Frequency Statistics**, on the next page. The before- and after-July 1999 periods are tabulated, as well as totals for the vehicle's entire life. The "Less I & PES" columns subtracted both *induced* and *prior event-same location* records from the totals. This reflects the "natural" event occurrence frequencies, having been adjusted for known induced and prior events. The frequency proportions, numbers of specified damage events divided by the total numbers of damage events, are shown in **Table V**. Because we really are interested in determining if any "natural" deterioration exists, **Table V** presents proportions only for the "Less I & PES" data (that is, induced and PES events were censored).

The following notes apply to **Tables IV** and **V** compilations**:**

- Data was current to August 22, 2004.
- No data was available for January–December 2002 and January–April 2003.
- Some events had more than one damage result (damage code); thus, TOTAL Damage Events exceeds the number of recorded events.
- All events coded beginning with a "K" implicitly include Kapton™ damage.
- Exposed conductor events implicitly include insulation damage.
- "Common cause" events are those for which more than one wire was damaged.

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* A broken wire 5 s after lift-off shut down two of the six Main Engine Controller computers.

Tables IV and **V** present wire damage event occurrences over the vehicle's lifetime, and includes the periods before and after the 1999 stand-down. Kapton™ damage and exposed conductors are the most prevalent damage modes. Wiring shorts occurred infrequently, but do exist. Exposed conductors and wiring shorts are those of greatest concern for the inadvertent reaction jet firing scenario.

Table IV. Summary Frequency Statistics
OV-103 Wiring Damage Events

		By Period				TOTAL Lifetime	
		(All)		Less I & PES			
		<July 1999	>July 1999	<July 1999	>July 1999	All	Less I & PES
# months =		183	47				
Total # wiring damage records		1303	1182			2485	
Total # wires affected		1626	1553			3179	
Damage Events:							
Kapton™ damage, unspec'd	KD	153	336	129	248	489	377
Kapton™ cracked, ring cracks	KR	127	192	107	176	319	283
Kapton™ dam., shield exposed	KS	170	169	155	135	339	290
Kapton™ dam., exposed conductors	KX	65	78	45	70	143	115
Wire broken	WB	132	37	111	29	169	140
Wire, conductor damage	WC	58	36	34	32	94	66
Wire damage, unspecified	WD	53	28	10	23	81	33
Wire chafed, or C. P. needed	WF	74	126	67	101	200	168
Wire, insulation damage	WI	85	10	58	9	95	67
Wire, jacket damage	WJ	46	6	40	4	52	44
Wire, shield damage	WS	144	67	117	64	211	181
Wire, shorted (short circuit)	WT	9	4	9	2	13	11
Wire, cut, or severed	WU	58	18	4	0	76	4
Wire, exposed conductor	WX	278	159	219	127	437	346
Total Damage Events*		1452	1266	1105	1020	2718	2125
Induced damage	I	208	85			293	
Induced, assoc. w/ prev. repair	IR	46	60			106	
Total Induced		254	145			399	
Common cause events		186	173	149	148	359	297

*** Total Damage Events exceeds Total # wiring damage records because many event records contained multiple damages ("codes") per event.**

Table V. OV-103 Wiring Damage Event Proportions, by Modes and Periods

		Less I & PES		
		<July 1999	>July 1999	Both
Damage Events:				
Kapton™ damage, unspec'd	KD	0.117	0.243	0.177
Kapton™ cracked, ring cracks	KR	0.097	0.173	0.133
Kapton™ dam., shield exposed	KS	0.140	0.132	0.136
Kapton™ dam., exp. conductors	KX	0.041	0.069	0.054
Wire broken	WB	0.100	0.028	0.066
Wire, conductor damage	WC	0.031	0.031	0.031
Wire damage, unspecified	WD	0.009	0.023	0.016
Wire chafed, or C. P. needed	WF	0.061	0.099	0.079
Wire, insulation damage	WI	0.052	0.009	0.032
Wire, jacket damage	WJ	0.036	0.004	0.021
Wire, shield damage	WS	0.106	0.063	0.085
Wire, shorted (short circuit)	WT	0.008	0.002	0.005
Wire, cut, or severed	WU	0.004	0	0.002
Wire, exposed conductor	WX	0.198	0.125	0.163
Induced damage*	I	0.143	0.067	0.108
Induced, assoc. w/ prev. repair	IR	0.032	0.047	0.039
Total Induced Damage		0.175	0.115	0.147
Common cause events*		0.135	0.145	0.140

* Induced and common cause events are exclusive of Damage Events

The Program has maintained that 85–90% of wiring damage on the vehicles is induced damage. These frequency statistics do not support that level of induced damage—only 12–18% (15% over the vehicle's lifetime) of wiring damage was identified as induced, according to database records and descriptions. These proportions are significantly different from what the Program has presented, and the difference likely will impact the fault tree model calculations. Also significant is that 14% of the wiring damage events are "common cause events"—those in which damage involves more than one wire.

For predicting future trends (including the fault tree events), it would be prudent to use the post-July 1999 frequency proportions, because these reflect the most current performance.

The **Table V** ("Both") data is presented as a Pareto chart in **Figure 4**. This is simply a visual representation of the wire damage event proportions over OV-103's lifetime—by NESC damage codes.

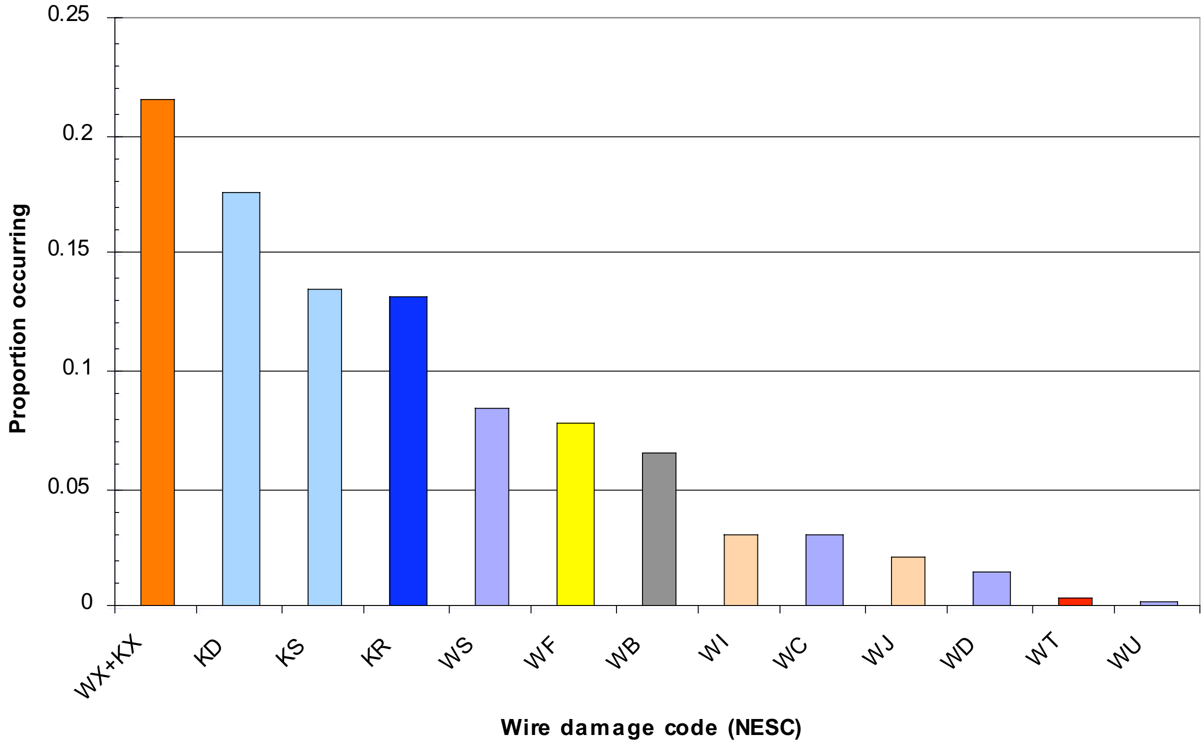

Figure 4. Pareto chart for OV-103 wiring damage events over the vehicle's lifetime. (See Table III for code descriptions).

Tables IV and **V** statistics can be deceiving. What are apparent similarities in occurrence frequencies between pre- and post-July 1999, in fact, occur over different time periods. Post-July 1999 covers a time approximately one fourth the pre-July 1999 period—47 months versus 183 months.

Table VI presents *"normalized"* occurrence frequencies, where for each period the numbers of occurrences are divided by the total number of months. This allows a less biased comparison between before- and after-July 1999 events. **Table VI** shows that for most all wire damage events (modes), the normalized occurrence *rate* (total occurrences divided by total months) increased by two to nine times after the July 1999 "wiring stand-down." Exceptions were *broken wires*, *Kapton™ damage-shield exposed*, *wire jacket* and *insulation damage*: broken wires and Kapton™ shield exposed remained the same, whereas jacket and insulation damage normalized rates decreased by about one half. All non-induced wiring damage events ("Total Damage Events") were detected at about three and one half times greater *frequency* (normalized) after the stand-down. This is *not consistent* with the Program-cited "six-fold increase" in detected wiring damage events, at least for OV-103.

Table VI. Normalized occurrence rates for OV-103 Wiring Damage Events, reported as event mean occurrences per month

		Less I & PES		
		<July 1999	>July 1999	Both
		Events per month		
Damage Events:				
Kapton™ damage, unspec'd	KD	0.71	5.28	1.64
Kapton™ cracked, ring cracks	KR	0.59	3.74	1.23
Kapton™ dam., shield exposed	KS	0.85	2.87	1.26
Kapton™ dam., exposed conductors	KX	0.25	1.49	0.50
Wire broken	WB	0.61	0.62	0.61
Wire, conductor damage	WC	0.19	0.68	0.29
Wire damage, unspecified	WD	0.055	0.49	0.14
Wire chafed, or C. P. needed	WF	0.37	2.15	0.73
Wire, insulation damage	WI	0.32	0.19	0.29
Wire, jacket damage	WJ	0.22	0.085	0.19
Wire, shield damage	WS	0.64	1.36	0.79
Wire, shorted (short circuit)	WT	0.049	0.043	0.048
Wire, cut, or severed	WU	0.022	0	0.017
Wire, exposed conductor	WX	1.20	2.70	1.50
Total Damage Events		6.04	21.70	9.24
Induced damage	I	1.14	1.81	1.27
Induced, assoc. w/ prev. repair	IR	0.25	1.28	0.46
Common cause events		0.81	3.09	1.73

IV. The STS Wire Inspection/Maintenance Process and OV-103 Wiring Damage Events

An initial analysis was performed on Program data [11]. These records compiled wire and interconnect short circuits over the Program's lifetime, for all vehicles, from the PRACA† database and were presented in May 2004. Because these data likely had multiple failure modes and "missing data," Crow-AMSAA‡ (CA) is the appropriate analysis tool [12]. Data covered 1983 through 2004 and listed wire damage and short (circuit) events. The resulting CA plot§ is shown in **Figure 5.**

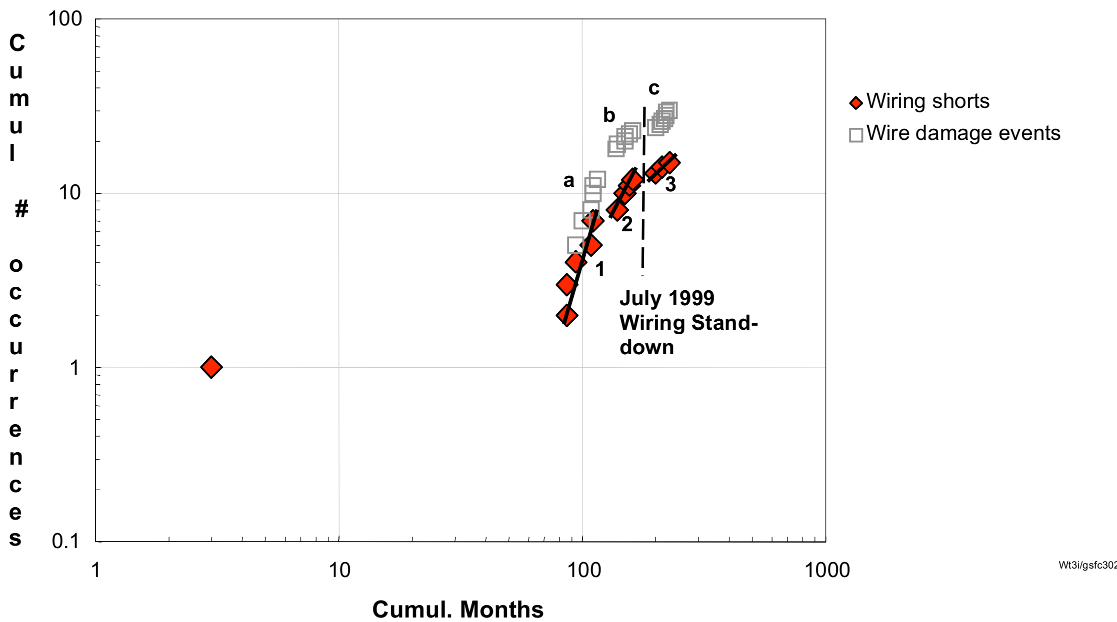

Figure 5. Crow-AMSAA plot of STS Orbiter Interconnect Short Circuits

The one wiring short circuit to the extreme left on the plot was a significant flight occurrence in March 1983. Other data were "missing" until approximately 86 months later.** The 1983 datum was suspended for the CA statistical analyses.

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† PRACA is the Problem Reporting And Corrective Action database.

‡ Crow-AMSAA (CA) analysis is an analysis tool originally developed to track reliability growth. It has found applications in tracking and trending reliability, safety, maintainability, and warranty events in numerous industries. It is particularly useful because it can handle "dirty data" including missing data, and mixtures of failure modes. CA "looks at" the entire system, which for our purposes means the wiring damage event occurrences and the inspection/detection/maintenance/reporting process. Straight lines on the plot define "stable" regions wherein the process follows a well-defined occurrence distribution; slopes indicate improvement (slope <1) or deterioration (slope >1) or no change (slope ~ 1). Jumps or cusps indicate some change has occurred in the process.

§ Analyses were performed using *SuperSmith Visual*™ software (Fulton Findings) and results ported to *Excel*™ (Microsoft).

** Data prior to ca. 1989 had not been entered into the electronic database; written records had been archived and were not researched.

For all wiring damage events (light gray, open squares), there were three "stable" regions:

Period	Slope	Interpretation
(a) 86–115 months	5.5	many more detected events per month
(b) 137–162 months	1.4	somewhat fewer, but still not static
(c) 199– 227 months	1.7	slightly worse than previous period

Wiring short circuits (filled diamonds) were also plotted, as a separate plot on the same graph, and these showed the following trends:

(1) 86–110 months	3.7	getting worse
(2) 140–162 months	2.7	a little better, but still worsening
(3) 199–227 months	1.1	much better, almost static

These data (May 2004) suggested that wiring degradation *may exist* in the Orbiter fleet. These CA results, however, could not within themselves definitively prove or disprove an increasing wire damage rate over the vehicle's life span. A brief report [13] recommended further detailed study to confirm details regarding wiring failure modes and character.

Detailed records for the Orbiter OV-103 were obtained with the intent of examining them to determine the existence of any wire effects over time. Initial analyses showed the data to be extremely "dirty" and difficult to analyze using normal Weibull methods. This is because the records reflect not only numerous wire failure modes,[††] but also differing levels of "detectability" during the Program's lifetime. This means that detection of wire damage is a "process variable" affecting the amount of wire damage discovered. Therefore, an initial analysis of the wiring inspection and maintenance process (system) was performed to understand wiring inspection and maintenance process variances. Again, CA is the appropriate tool (see the second footnote on the previous page).

The initial CA analysis, shown in **Figure 6** evaluated all wiring damage events using the vehicle delivery date (10 November 1983) as the "zero," or starting, time. As seen in the data, several jumps and cusps exist. Significant changes occurred during the *Challenger* return to flight (RTF), one Orbiter Major Maintenance (OMM) activity (J2), the July 1999 wiring stand-down and the *Columbia* stand-down. After extensive analysis, no "stable" regions were evident, except for the first 28 months—the period before the *Challenger* accident. The first four flights (of OV-103) exhibited a β (slope) slightly less than 1 (0.9), indicating that slightly fewer wiring damages per flight were detected during Orbiter processing. The next two flights (through #06) yielded more detected damage, as the slope increased to 1.3–1.4. There was a marked increase in detected damage during the *Challenger* RTF period, with a slope of 3.1; however, the statistical fit was poor ("p%" was less than 10%). After returning to flight, OV-103 experienced a decrease in the detected damage "rate" (slope 0.8) through flight 10, and then detected damage increased again. The "noise" in the data precluded a good statistical fit, even after censoring "jumps" during *Challenger* RTF, J1, J2, and the 1999 stand-down. Nonetheless, the general trend after about 80 months (flight 10) is an increase in detected wire damage events (slope ~1.7). Differences in "detection rates" likely are influenced by programmatic events or activities.

[††] Weibull analysis focuses on one failure mode at a time.

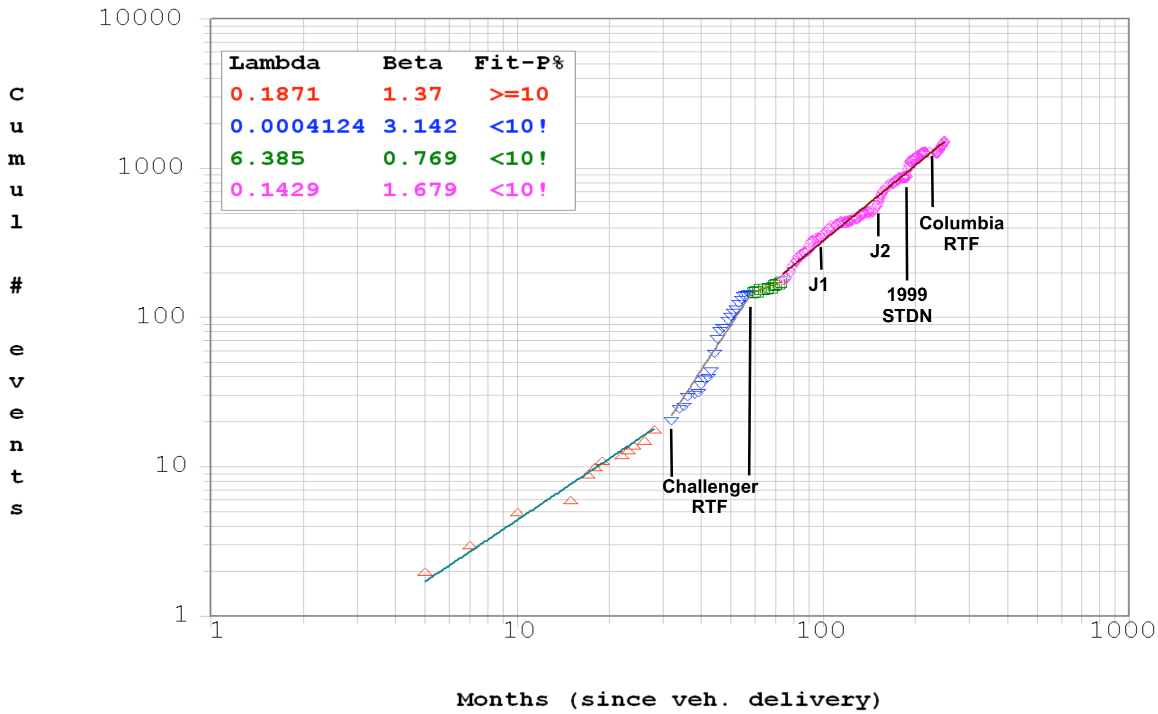

Figure 6. Crow-AMSAA plot of all *detected* OV-103 wiring damage events, plotted by months since vehicle delivery

The **Figure 6** data do not provide a good statistical basis for making any definitive conclusions (because of the poor statistical fit beyond 30–40 months).

Because the STS vehicles are "processed" between each flight, it seemed logical to plot wiring damage data by "vehicle flight number." This is the time between a given launch and just before the subsequent launch—it includes the flight time through landing (for any wire damage anomalies recorded during flight) and the following processing time (maintenance and inspections) leading up to the next flight. Jumps in damage events occurred during or after significant vehicle events (**Figure 6**), for example, after the *Challenger* stand-down, two OMM activities ("J1" and "J2"), and the 1999 stand-down. To accommodate plotting cumulative data for these activities, the data was compiled using "relative flight number." The flight number after J1 is incremented by 1, after J2 by 2, and after the 1999 stand-down by 3—so there appears to be 33 flights on the plot for OV-103's actual 30 flights. This CA plot by flight cycle is presented in **Figure 7**, below. Numbers adjacent line segments are the slopes (**β**'s).

These data, in one sense, are taking a "coarser" look at the wiring inspection/maintenance process, because cumulative damage events are summed over entire flight cycles. Nonetheless, good statistical fits for various flight "segments" resulted throughout OV-103's lifetime. Likely, the effect is akin to moving average computations, which tend to smooth out "noise" in data.

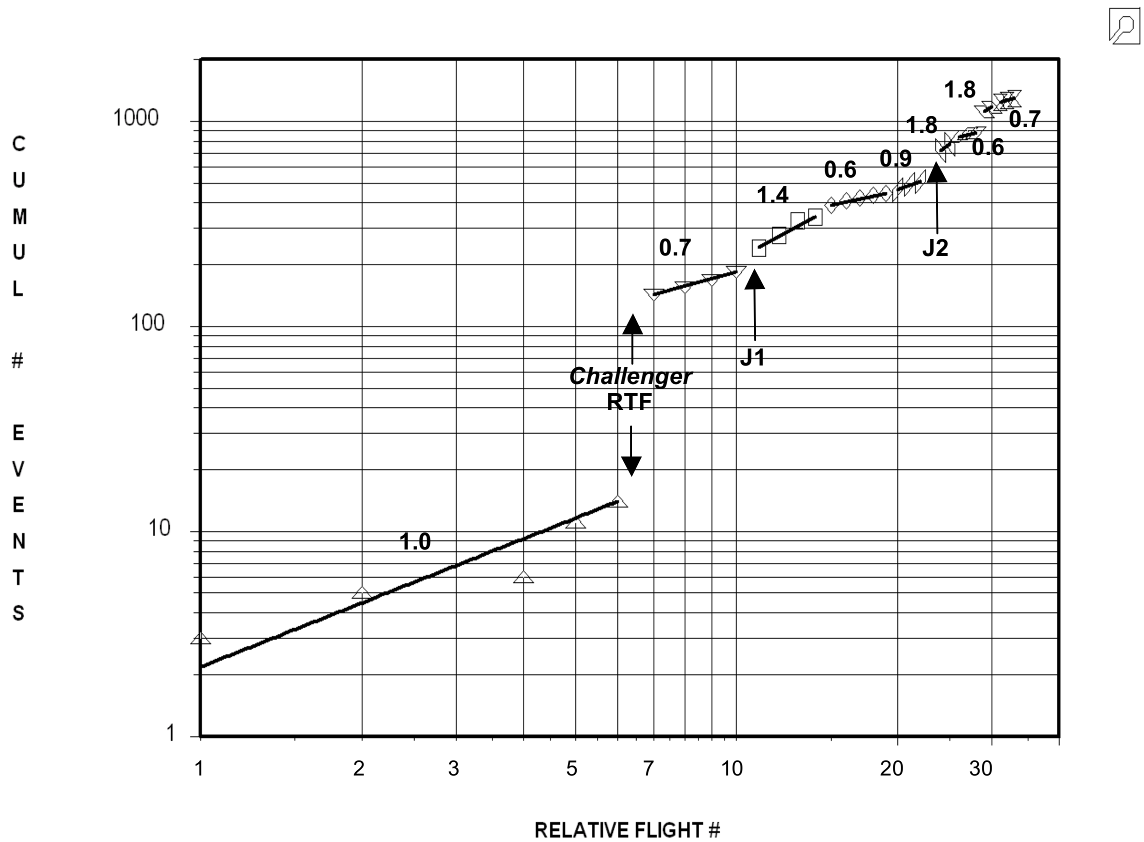

Figure 7. Crow-AMSAA plot of OV-103 *detected* wiring damage events by vehicle flight number. Numbers above and below lines are slopes. "Relative flight numbers" are vehicle flight numbers incremented by 1 and 2 after J1 and J2, respectively.

In this plot, one can see the jumps at *Challenger* RTF, J1, J2, and the 1999 stand-down. Post-*Columbia*-accident data was not plotted. The initial (up to *Challenger*) detection rate was static (slope ~ 1), compared to the 1.4 seen in the "by month" data. After *Challenger* RTF, the per-flight data exhibited the same slope of decreased wire damage detection (0.7 vs. 0.8 for the "by month" data) until the J1 OMM activity. After J1, detected events increased for four flights and then decreased for the next five flights (0.6 slope). There was an increase in detected events for flights 19 through 21. An expected jump occurred for J2 OMM. Then detected events changed between increased detection (slope 1.8) and decreased detection (slope 0.6) until the 1999 stand-down. It subsequently followed the same pattern after the 1999 stand-down—increased detection (1.8) then reduced detection (0.7). The inspection/detection process appears to oscillate between enhanced and diminished detection since the J1 OMM activity.

The above plot is a "traditional" CA plot, in which it is easy to see improvement or deterioration and jumps or cusps within trends signifying process changes. In fact, if a process exhibits "stable" behavior (one fitting a straight line for "a long time"), future performance can be read directly from the plot. For example, if the OV-103 wiring damage detection process was *stable*,

future performance could be predicted by a simple linear extrapolation to future flights. This, of course, assumes that no jumps or cusps occur within the future period.

Another way of looking at the same data is to plot the events as an *occurrence rate* (failure rate if the plotted events are failures) versus cumulative time (flight cycles, in our case). This is shown in **Figure 8**.

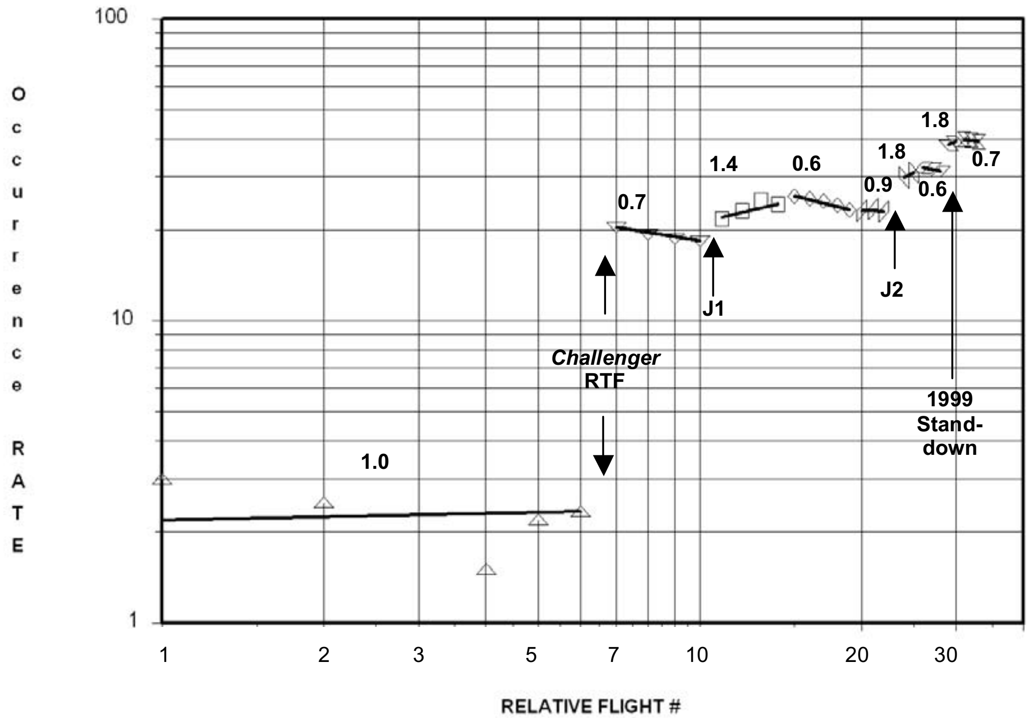

Figure 8. OV-103 Wiring Damage Events (By Flight Cycle) Plotted as Occurrence Rates, from CA Plot

The **Figure 8** data are the event occurrence *rates* (analogous to failure rates) plotted per (cumulative) flight cycle. For this presentation, a "flat" line means the process is static (not changing with time), an upward slope (to the right) means events are occurring more frequently with time (more events detected per flight cycle), and a downward slope means fewer events occurring with time (fewer detected per flight cycle). This plot reflects the same trends shown in the "traditional" CA plot (**Figure 7**) and it is easier to distinguish between "improvement" and "deterioration."

A significant finding is that the claimed six-fold increase in wiring damage detection after the 1999 stand-down is not justified. Prior to the stand-down (the 1.8 and 0.6 slopes before relative flight 28—actual flight 26), the wiring event detection rate was approximately 30 events per cycle. After the stand-down (1.8 and 0.7 slopes), it was about 40 events per cycle, an increase of only 1.3 times. Another significant finding is that the detected event occurrence rate gradually increased after the *Challenger* RTF: the detected event rate changed from about 20 per flight to

40 per flight. This gradual increase likely represents an increase in wiring damage related to its life span, because the "oscillating" (up and down short term rates) reflect variances in "detectability," those caused by "systematic," or inspection/maintenance process, effects.

A third significant finding from both **Figures 7** and **8** is OV-103 wire damage detection is *not stable over long times*—the longest stable "runs" were five flight cycles, before the trend either jumped or changed slope. (Of course, we understand reasons for some of these "jumps").

As surmised above, changes in wire damage detection between the various OV-103 flight cycles likely are related to programmatic (systematic) changes implemented throughout the vehicle's lifetime. The Program may be able to provide interpretations of these variances (from their knowledge of the personnel, process, and technical changes throughout the Program's lifetime).

V. OV-103 Wiring Damage by Failure Modes

The database listing all failure modes (used for the above CA) provided data to analyze wiring damage characteristics for OV-103. It already had been categorized by wire damage modes, so relevant failures or faults (i.e., damage events) for *each mode* were extracted for Weibull analyses. "Failure," for these analyses, means "wire damage," or, more precisely, wire damage by a specific mode (exposed conductors, short circuits, etc.). Failure times are reasonably exact for broken wires and short circuits—these were detected as operational or test anomalies. Other modes have more approximate times—damage had occurred before the report date.

Non-failed wires must be accounted to determine realistic probabilities. Each vehicle has 147–150 miles of wiring. But only 10–15% is accessible for inspection. Thus, the "sampling" population is 10% of 150 miles, or approximately 950,400 inches of wiring. Each damage event was assumed to affect one inch of wire. (This may be conservative; however, numerous records indicated cases where several inches of wiring had been damaged). For each analysis, non-failed wires were 950,400 less the number of failed wires. As non-failed wires had survived to the last report date (249 months), suspension times of 250 months were assigned. Large numbers of "right suspensions" (i.e., non-failed wires) move the plots down the probability axis. Even if the "one-inch" assumption is not exactly correct, a different assumed affected length will only raise or lower the Weibull plot along the probability (y) axis; the slope will be unaffected [7]. For example, one analysis yielded β = 1.52 and η = 389,800 months using the one-inch assumption. Changing to a 0.5 inch affected wire length gave β = 1.52 and η = 508,700 months.

Note that the characteristic life parameter (η, or eta) [‡‡] for all these Weibull data are in *months*; the slope parameter (β) is unitless.

A. Wiring Short Circuits

The first analysis was of wiring short circuits, as these would have the greatest potential adverse effect on the inadvertent firing scenario. For OV-103 there were 11 events involving 16 wires

‡‡ For those unfamiliar with Weibull statistics, η is analogous to a median; it is the point at which 63.2% of the population has failed (cumulative failures).

over a period from 46 to 240 months. The first four events all occurred between 46 and 53 months during the *Challenger* RTF. An initial Weibull plot showed an apparent bimodal distribution, with these first five wire failures (four events) occurring as one set having a high β (6.0). Interval analysis was tried, but yielded a poor fit. Four events occurring "almost simultaneously" (compared to the entire 300 months of the time axis) is analogous to "inspection data" [14], where failure points appear "stacked." Using the "interval option" produced a poor fit (3 to 6% p-value estimate, pve); however, interval data was simulated by suspending the first three failures and using the "standard" analysis. This produced the Weibull plot shown as **Figure 9**.

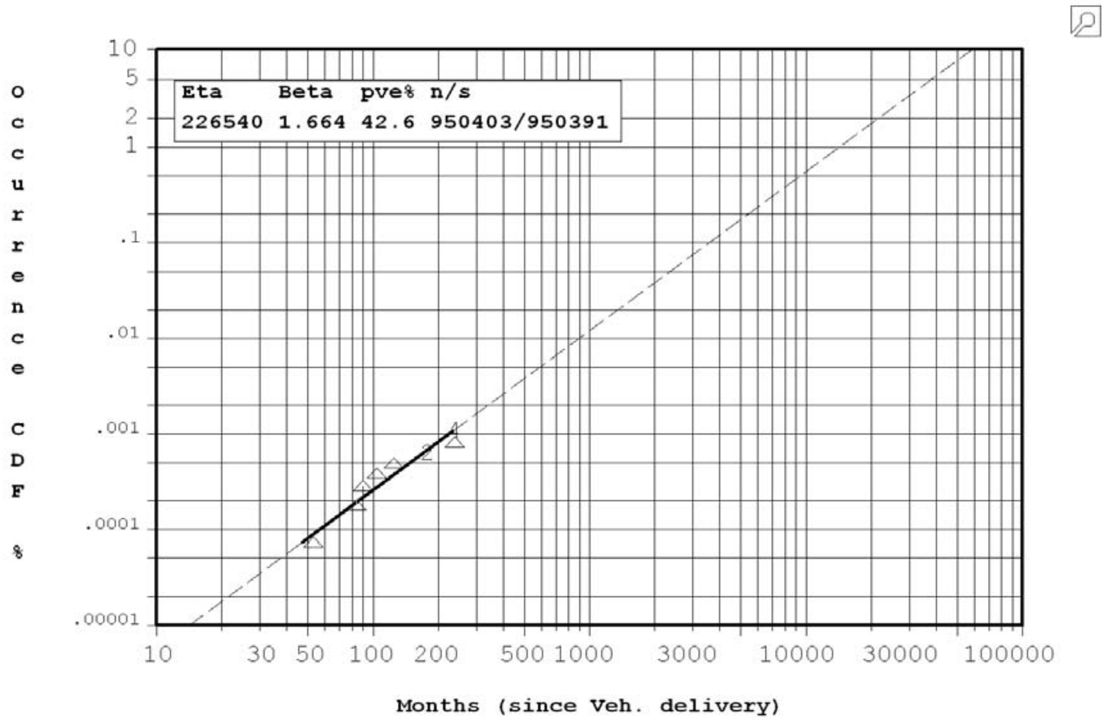

Figure 9. Weibull plot of OV-103 wiring short-circuit events. The Weibull slope indicates early wear-out failures are occurring.

The Weibull parameters (β = 1.7 and η = 226,500 months) indicate an early wear-out failure mode, that is, the failure rate is increasing with time, albeit at a slower rate than "true" wear-out (β greater than 4). Thus for wire short circuits, there *is* a failure (or occurrence) rate increasing with time. The above Weibull parameters can be inserted into the fault tree model to replace the existing CFR assumption; this will more accurately reflect wire short circuit occurrences, at least for OV-103.

B. Wiring Exposed Conductors

Data for both "wire with exposed conductors" and "Kapton™ damage with exposed conductors" (WX and KX codes) were combined to derive this failure distribution. Both modes create "exposed conductors," a primary (bottom-level) event for the inadvertent firing scenario. The initial plot, using all 342 exposed conductor events, was very "dirty" and not solvable, even after numerous attempts at suspending various portions. The plot was not unlike that of **Figure 6**'s

data. Abernethy suggests the Kaplan-Meier (K-M) survival function as appropriate for "…large data sets of either or both failures and suspensions" [15]. The K-M survival function has been used in the medical industry for years. It is *non-parametric*, not requiring a fit to any distribution. Because it computes "survivals," its complement is a "failure" function, which can be analyzed using the Weibull distribution. The exposed conductor data were recompiled to a K-M format, using accumulated "survivors" (total number of wires less the "failed" and censored ones) at each flight cycle.

The resulting K-M Weibull fit was excellent, yielding **Figure 10**. Exposed conductors initially fail as a near-CFR distribution (β = 0.9) until about 78 months (six and a half years) when early wear-out failures (β = 2.2) "take over." [Exact parameters from the plot can be used in the fault tree calculations or other predictions].

Exposed conductors are a primary concern regarding the wiring contributions to inadvertent RJD firing. If the Program replaces RJD control wiring (as proposed in the NESC briefings), only randomly occurring exposed conductor failures would be expected for approximately six and a half years of vehicle life after the wiring is replaced. (This assumes that the replaced wiring is equivalent to the existing wiring in the vehicle).

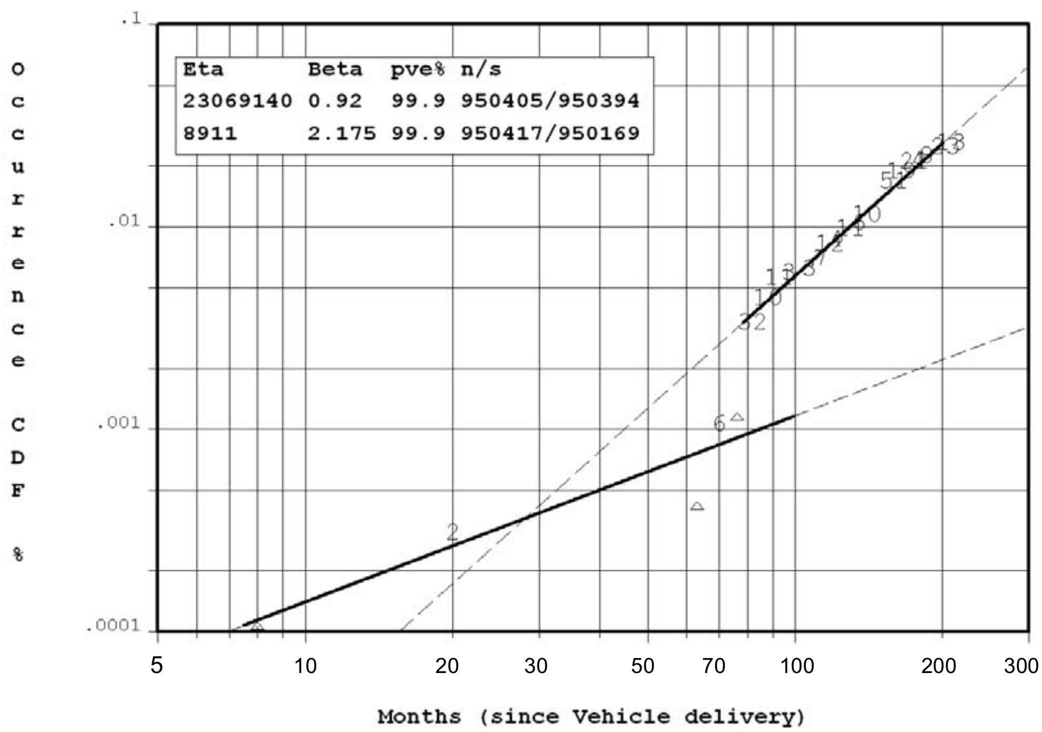

Figure 10. Weibull plot of Kaplan-Meier data for OV-103 exposed conductor events. Earlier distribution is a near-random failure rate; later distribution is early wear-out.

C. Kapton™ Cracks and Ring Cracks

Data for Kapton™ cracks and "ring" cracks (KR code) were analyzed using the K-M function (see **B**, above). The first analysis, using all data as one set gave a poor fit ($r^2 = 0.74$), however, the data pattern was similar to exposed conductors, above. There was an initial "flat" distribution ($\beta = 0.4$ $\eta = 2 \times 10^{15}$ months) out to about 91 months followed by an early wear-out distribution ($\beta = 1.9$ $\eta = 23{,}320$ months). The Weibull plot is shown as **Figure 11**.

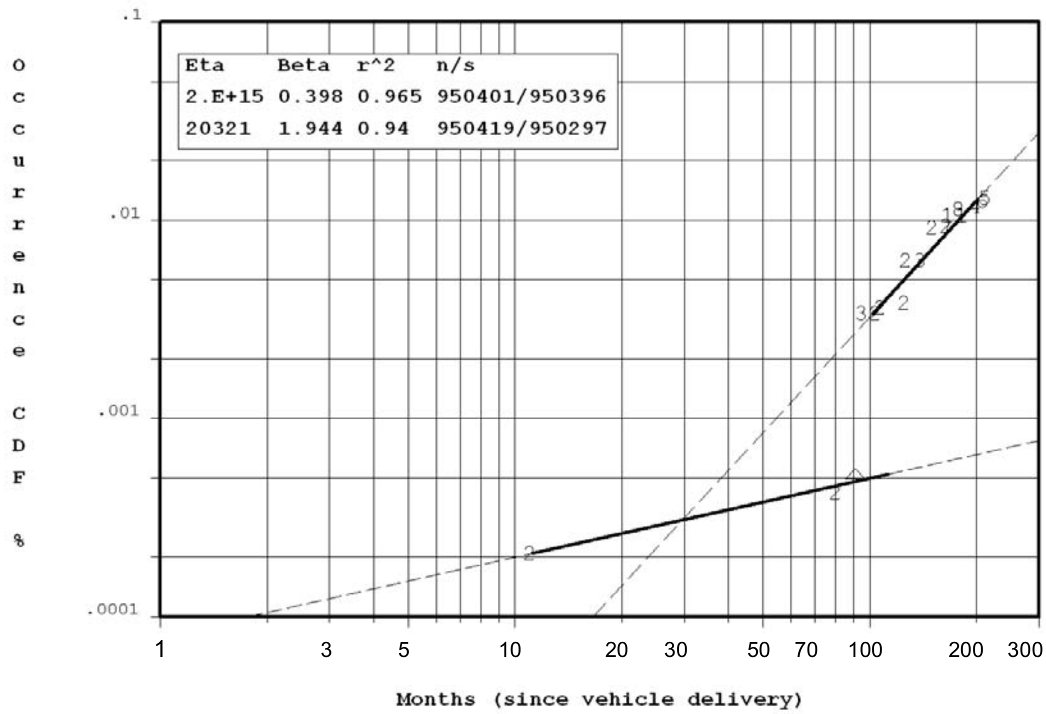

Figure 11. Weibull plot (K-M) for OV-103 Kapton™ cracking and ring cracks. Early failures are infant mortals; later are early wear-outs.

D. Other Kapton™ Damage—Exposed Shield and Not-Specified

NESC coding had categories for "Kapton™ damage that exposed wire shielding" (KS) and "Kapton™ damage unspecified" (KD)—damage for which the description did not specify in enough detail to assign the event to one of the other categories. As these were the two remaining Kapton™ damage categories, they were combined and analyzed using a Weibull/K-M plot. For these modes, the data gave a good fit (0.95 r^2), although failure points deviated from the fit line above 90 months. Dividing the data at less than 89 months and greater than 93 months improved the "upper" fit to 0.99 and the weighted composite fit to 0.98. Either fit is equivalent, because the β's and η's were similar for all:

		β	η	r^2	
Fit using all data:		2.88	2630	0.95	
Fit separating data:	(a)	2.89	2770	0.99	
	(b)	2.92	2700	0.94	(0.98—weighted composite)

The plot using the "separated" data is shown as **Figure 12**. In this case, there was no initial "flat" distribution—early wear-out events commenced at about 60 months.

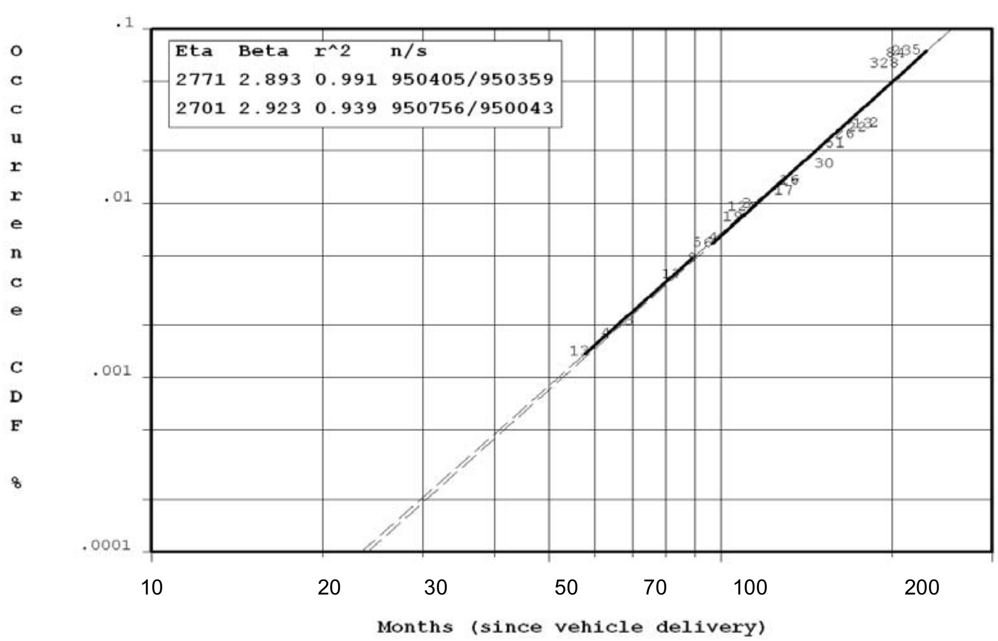

Figure 12. Weibull Plot (K-M) of Other Kapton™ Damage Events (KD and KS)

E. Wire Chaffing Events

Wire chafing events include instances where inspectors discovered either wires that had been chafed or wires that required chafe protection (that is, there were indications that chafing protection would be needed to prevent further damage). These were analyzed using a Weibull plot of the K-M survival function for wire chafe events and the results were similar to other damage modes: a "flat" Weibull (infant mortality) followed by early wear-outs after about 80 months. These results are shown in **Figure 13**.

F. Broken Wires

A broken wire was involved in at least one significant flight event (STS-93, see p. 7). Of 134 broken wire events, nearly half (64) were associated with ground lug or ground wire failures. All broken wires were analyzed using the K-M function and exhibited the initial "flat" Weibull seen in most other failure modes. However, during *Challenger* RTF and for subsequent flights until

the first OMM (J1), broken wire failure incidence increased significantly. These returned to the early wear-outs ($\beta \sim 2.3$) seen for the other modes after J1. The plot is **Figure 14**.

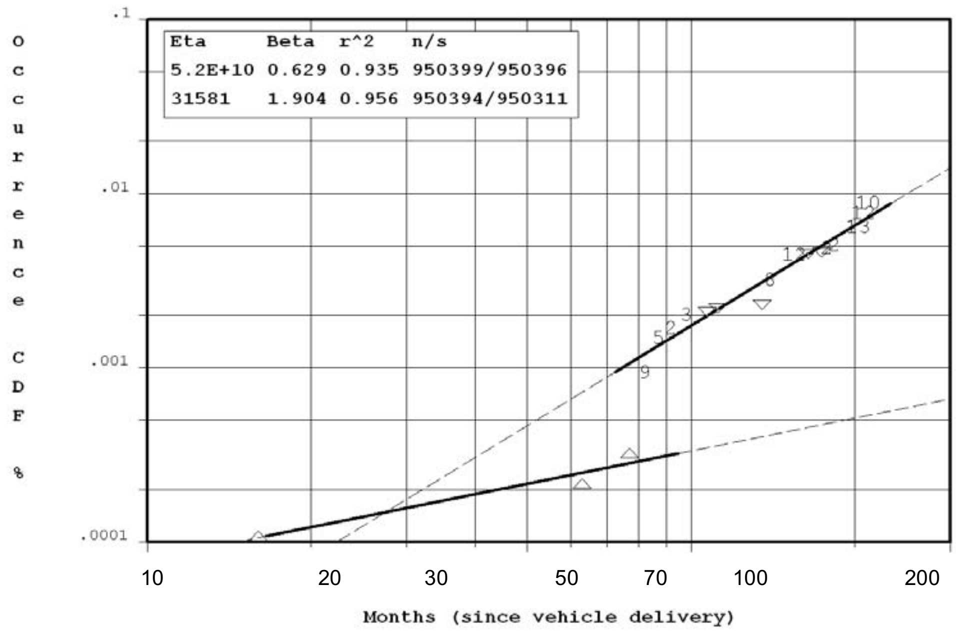

Figure 13. Weibull Plot (K-M) of Wire Chaffing Events

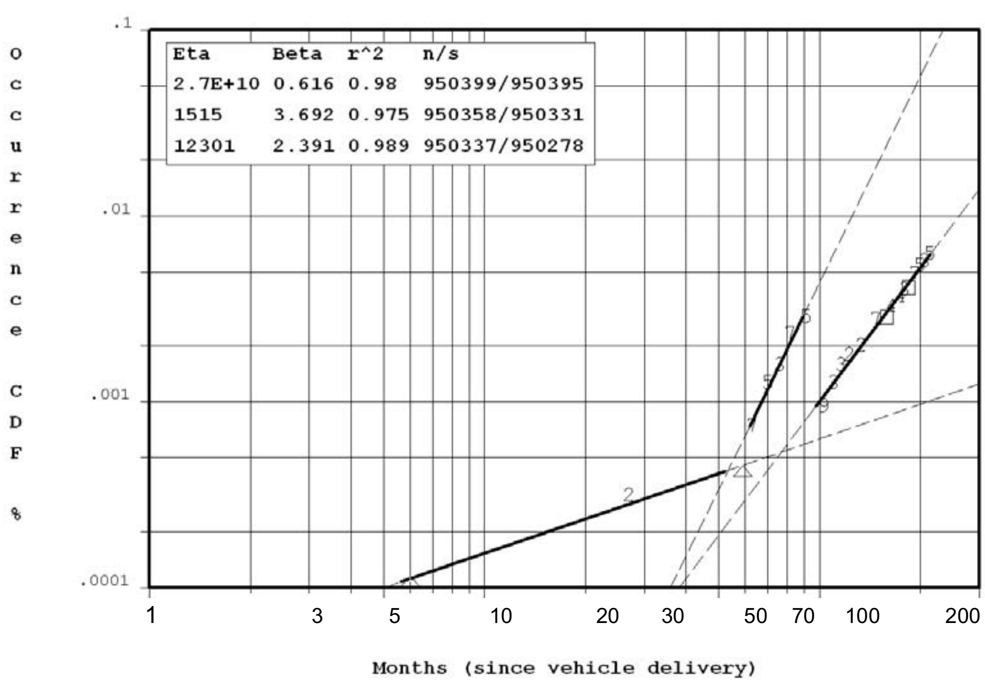

Figure 14. Weibull (K-M) Plot of Broken Wire Events

All failure modes evaluated (wiring short circuits, exposed conductors, cracking and ring cracks, Kapton™ damage and exposed shielding from Kapton™ damage, wire chafing, and broken wires) exhibited early wear-out failure modes, indicating that the wiring in OV-103 does experience an increasing damage occurrence rate with time. For all modes, except short circuits and Kapton™ damage/Kapton™ damage-exposed shielding, the early wear-out failures (or occurrences) began after initial periods of either CFR or infant mortality. These initial periods ranged from about 60 to 95 months (five to eight years). The two modes of most concern for the inadvertent scenario, short circuits and exposed conductors, showed the following Weibull parameters:

		β	η (in months)	fit
Short circuits:		1.66	226,540	42.6% (pve)
Exposed conductors:	(a)	0.92	23,069,140	0.87 (K-M, r^2)
	(b)	2.18	8911	0.99 (K-M, r^2)

VI. Discussion

Compiled frequency statistics showed that exposed conductors and Kapton™ damages occurred most often over OV-103's lifetime (about two thirds of all damages). Wiring short circuits occurred infrequently (only 0.5%), but did occur. Both exposed conductors and short circuits are relevant to the inadvertent firing scenario.

Also significant, from the wiring damage frequency compilation, was that 14% of the events involved more than one wire. This proportion was consistent between the pre- and post-July 1999 periods (13.5% compared to 14.5%, respectively).

Induced damage, caused by *identifiable* inspection and maintenance activities or other causes, occurred as 15% of the cited wiring damage events over the vehicle's lifetime (18% before July 1999, 12% after July 1999). This varies considerably from the "85 to 90% of induced damage" cited by the Program. This study classified induced damage *only through the cited report descriptions*. Should the Program choose to more accurately determine induced wiring damage event frequency, inspection/maintenance reporting changes would be recommended to better track such events. Likely causal factors for "induced" damage would be related to maintenance activities; better tracking of what wires (and what wire locations) are inspected, repaired, and modified could improve identifying induced damage events. Later records do track specific wires and locations for each damage event, but for earlier periods these are sketchy.

Analyses of the OV-103 wiring inspection and maintenance process (using CA analysis) showed the process is *not stable* over long periods of time. That is, numbers of detected wiring damage events do not follow a consistent "accumulation" pattern between various segments of sequential flight cycles. The longest "run" before a jump or slope change was five cycles (two occurrences, one being before the *Challenger* accident). Likely these process variances are related to programmatic changes affecting the maintenance and inspection process. Some of the jumps in the trend can be explained by enhanced vigilance, such as during *Challenger* RTF, OMM

Activities (J1 and J2), and the 1999 wiring stand-down. After the J1 OMM activity, the inspection/maintenance process oscillates between enhanced detection (CA slopes 1.8–1.9) and decreased detection (slopes 0.6–0.7). Implementing process improvements until the wiring maintenance/inspection exhibits "stable" behavior (a consistent CA slope over 8 to 10 flight cycles) would improve the "predictability" of the process. There was also a gradual increase in detected events since *Challenger* RTF —from about 20 to about 40 per flight cycle prior to the *Columbia* stand-down.

The Program has cited a six-fold improvement in wiring inspection and maintenance after the 1999 wiring stand-down. The OV-103 CA data do not support that level of increase in wiring damage detection. The pre-July 1999 detection rate (per flight cycle) was approximately 30 and after the stand-down 40. This is an increase of only 1.3 times. This apparent paradox compared to Section III's frequency statistics is related to how the statistics were calculated for each. The proportions presented in Section III were more approximate, since those were derived by simply dividing total events by total months for each of two non-equivalent periods. CA statistics accumulate occurrences by flight over the vehicle's lifetime and thus provide more detailed and accurate results.

The Program certainly should consider implementing CA as a tracking tool for STS wiring damage trending. The data in this report focused only on OV-103. Similar analyses should be performed for the other two vehicles. The trending chart could be used as on-going prediction tool, if the wiring inspection/maintenance process demonstrates "stable" behavior.

Wire damage occurrences versus time were evaluated by separating the wiring damage events by failure modes and analyzing each mode independently using Weibull plots. All modes exhibited early wear-out behaviors, that is, Weibull slope parameters (β's) greater than one indicating failure (occurrence) rates increasing over time. Four of the six evaluated modes also showed infant mortality or random-failure-rate behavior early in the life of OV-103; these "flat" distributions occurred up to 60 to 95 months of vehicle life. These results are summarized in **Table VII**.

The Weibull results are essentially a sampling of wiring damage in the vehicle, because not all wiring is available for inspection and likely not all damage is detected. Four of the six evaluated modes exhibiting the same "pattern" is very strong evidence that wire damage occurrences increased over OV-103's life span. For this to not exist, the Weibull slopes would all have to be near 1.0. These results follow from what would be expected for wiring that degrades over time. It does not degrade instantaneously. There is an "incubation" period of about 60 to 99 months (in OV-103) before early wear-out failures begin to accumulate. The incubation period varies according to the failure mode. This also is not unexpected because different modes would manifest by different mechanisms.

Because wire damage is increasing in OV-103, similar investigations are recommended for the other two vehicles' wiring. Should they also exhibit the same or similar wire damage patterns, the Program then should institute a careful review of all "CRIT 1-1" wiring and carefully monitor its "health." It is unrealistic to expect replacement of all the wiring in each vehicle, but steps should be taken to minimize the risks for that wiring critical to mission success.

Table VII. Summary of Weibull Parameters by Failure Mode

Mode	Period* (mos.)	β	η (months)	Fit	precise β
Wiring short circuits	46–240	1.7	226,500	Weibull – 42.6% pve	1.664
Exposed conductors	(a) 7–76	0.9	23,069,100	Weibull/K-M - 0.870 r^2	0.920
	(b) 82–208	2.2	8910	Weibull/K-M - 0.987 r^2	2.175
Kapton cracks & ring cracks	(a) 11–91	0.4	2.0 e+15	Weibull/K-M - 0.965 r^2	0.398
	(b) 99–211	1.9	20,320	Weibull/K-M - 0.940 r^2	1.944
Other Kapton damage (KD & KS)	(a) 57–89	2.9	2770	Weibull/K-M - 0.991 r^2	2.893
	(b) 93–221	2.9	2700	Weibull/K-M - 0.939 r^2	2.923
Wire chaffing	(a) 16–77	0.6	5.2 e+10	Weibull/K-M - 0.935 r^2	0.629
	(b) 82–212	1.9	31,580	Weibull/K-M - 0.956 r^2	1.904
Broken wires	(a) 6–59	0.6	2.7 e+10	Weibull/K-M - 0.980 r^2	0.616
	(b) 63–91	3.7	1520	Weibull/K-M - 0.975 r^2	3.692
	(c) 103–213	2.4	12,300	Weibull/K-M - 0.989 r^2	2.391

* Period refers to the time over which failure data were reported.

VII. Conclusions and Recommendations

1. For the civil aircraft investigated from the FAA "AIDS" database, which included both general aviation and air carrier and commercial aircraft, wiring failure incidents showed Weibull slopes of 1.6 to 1.9 and included shorted (short circuited), chafed and broken wires. This indicated wire failure incidents increased as these aircraft accumulated operating time. (Fleet, or in-service, failure probabilities were not calculated).

The following conclusions apply to OV-103's wiring:

2. Most frequently occurring wire damage events were exposed conductors and Kapton™ damage (four different modes—damage, unspecified; cracks and ring cracks, damage with exposed shielding, and damage with exposed conductors).

3. Induced damage to wiring was observed to be only 0.15 of all damage, compared to the Program's cited 0.85 to 0.90 occurrence proportion. This proportion changed from 0.18 before, to 0.12 after, July 1999.

4. "Common cause events," those in which more than one wire was affected, were 0.14 of damage event occurrences.

5. The wiring inspection and maintenance process, as measured by detected wiring damage events per flight cycle, was not stable for longer than 5 flight cycles. The first stable

occurrence was the six flights prior to the *Challenger* accident; a subsequent five cycle run occurred during flights 15 through 19. The process oscillated between enhanced detection and diminished detection after the J1 major maintenance.

6. The six-fold improvement cited for wiring inspection and maintenance after the July 1999 stand-down is not confirmed by these data. The CA occurrence rate plot shows a change from 30 to 40 events (per flight cycle) before and after July 1999. These results suggest an improvement of about 1.3 times.

7. The CA occurrence rate plot also shows a gradual increase in detected events from after *Challenger* RTF up to the *Columbia* stand-down. This increase overlays the "oscillating" detection occurrences; likely it reflects wire degradation.

8. Weibull analyses of OV-103 wire damage events shows that ***wire damage events increased over time.*** All six modes analyzed exhibited Weibull slopes of 1.7 to 3.7 <u>*after*</u> 57 to 99 months. For exposed conductors, a near constant failure rate existed for the first 76 months; for cracks and ring cracks, failures occurred as infant mortality up to 76 months; for wire chafing, infant mortality to 77 months; and for broken wires, infant mortality to 59 months. Weibull slopes for all "later" failures indicated early wear-out failure modes are occurring through 213 to 240 months of vehicle life. (See **Table VII** for details, by failure modes analyzed).

9. The Weibull parameters for the two modes most relevant to the inadvertent firing scenario are:

Wiring short circuits:		$\beta = 1.7$, $\eta = 226{,}500$ months
Exposed conductors:	initial (a)	$\beta = 0.9$, $\eta = 23{,}069{,}100$ months
	later (b)	$\beta = 2.2$, $\eta = 8910$ months

10. Should the Program replace the RJD wiring (per NESC's recommendation), the replaced wiring will "revert" to the initial (before early wear-out) distributions and pose less risk for up to five to eight years, depending on the wire failure mode. This does not mean the newly installed wiring will be failure-free; it means it will follow a different failure law (per **Table VII**) after the wiring is installed. This assumes that the newly installed wiring is equivalent (installation, process, performance) to the existing wiring in OV-103.

Recommendations:

1. The NESC fault tree model should be revised to reflect the observed wiring degradation over time, cited herein.

2. Wiring damage for the other two STS vehicles should be evaluated by the same protocols as this report. These would include CA evaluations of the wiring inspection-maintenance processes and Weibull analyses by failure modes. A detailed description of data

compilation and analyses can be documented to assist the Program in performing these evaluations.

3. Using CA techniques to trend wiring damage data would assist the Program in accurately tracking and assessing the wiring inspection-maintenance process for the other vehicles. The goal would be to get the wiring inspection-maintenance process “stable,” so that it exhibits a defined occurrence distribution. Ideally, this distribution would have a CA slope of 1.0 or less, indicating either a static process or one which is improving. There must be a positive correlation between damage events detected and damage events existing. Likely, CA techniques also would benefit the Program in other areas of endeavor.

4. Should the Program choose to accurately track induced damage events, wiring damage inspection-maintenance process revisions likely are needed. The goal would be to positively identify and track damage occurrences caused by “non-natural” events or actions.

5. Wire damage occurrences increased over time for OV-103. Recommendation #2, if implemented, will determine if it also exists in OV-104 and OV-105. If wire degradation exists in all three vehicles, the Program should undertake a risk assessment to determine which wiring is critical to the successful operation of the vehicles. This “at risk” wiring should be closely tracked and monitored to prevent future undesirable events.

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14. ABSTRACT
This study investigated the Shuttle Program's belief that Space Transportation System (STS) wiring damage occurrences are random, that is, a constant occurrence rate. Using Problem Reporting and Corrective Action (PRACA)-derived data for STS Space Shuttle OV-103, wiring damage was observed to increase over the vehicle's life. Causal factors could include wiring physical deterioration, maintenance and inspection induced damage, and inspection process changes resulting in more damage events being reported. Induced damage effects cannot be resolved with existent data. Growth analysis (using Crow-AMSAA, or CA) resolved maintenance/inspection effects (e.g., heightened awareness) on all wire damages and indicated an overall increase since Challenger Return-to-Flight (RTF). An increasing failure or occurrence rate per flight cycle was seen for each wire damage mode; these (individual) rates were not affected by inspection process effects, within statistical error.

15. SUBJECT TERMS
wiring damage, PRACA, causal factor, damage event, Crow-AMSAA, Weibull, aerospace vehicles, Kapton, aircraft wiring

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